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NASA TN D-4668

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**EFFECT OF CRYSTAL TRANSFORMATION AND
ATOMIC ORDERING ON FRICTION AND WEAR
OF TWO COBALT-BASE ALLOYS IN VACUUM**

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

The effect of crystal and order-disorder transformations on friction and wear for Be-Co and FeCo alloys were studied in sliding friction experiments in vacuum at elevated temperatures. The results show that friction increases fourfold for the beryllium-cobalt alloy during transformation and that friction remains high until the reverse or cooling transformation occurs. The friction and wear of Be-Co are markedly superior to 440-C stainless steel. The order-disorder transformation in FeCo increases friction by a factor of 30 and also significantly increases wear. Increased sliding speed and loading affect the transformation. The friction behavior during heating is in good agreement with the type of order-temperature relation in FeCo.

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SUMMARY

Experiments were conducted to determine the effect on ^{Co}friction and wear or ^{Co}crystal transformations in a 10-atomic-percent ^{Co}beryllium - 90-atomic-percent cobalt (Be-Co) alloy and the ^{Co}order-disorder transformation in the 50-atomic-percent ^{Fe}iron - 50-atomic-percent cobalt alloy (FeCo). Runs were made in vacuum from 10^{-11} to 10^{-7} torr (10^{-9} to 10^{-5} N/m²) and to temperatures of 1800° F (982° C) with a 0.476-centimeter radius rider sliding on a 6.5-centimeter diameter flat disk. Sliding velocities were from 0.003 to 205 centimeters per second.

The results with Be-Co show that friction increases by a factor of 4 during the hexagonal to face-centered-cubic crystal transformation, but the temperature at which this occurs is higher than for pure cobalt. This higher temperature results in an increase in the usable temperature range for unalloyed cobalt during sliding. The friction for Be-Co remains high until the reverse or cooling transformation (face-centered-cubic to hexagonal) occurs. At room temperature, the friction and wear properties of Be-Co are markedly superior to 440-C stainless steel.

The order-disorder transformation in FeCo results in a thirty-fold increase in friction, and the wear also significantly increases. Increasing sliding speed or load lowers the temperature at which the friction begins to increase. The friction increase with temperature is in good agreement with the variation of order for a second degree order type.

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INTRODUCTION

The friction and wear of materials in a vacuum environment are influenced by many mechanical properties. These properties are, in turn, related to such fundamental factors as crystal structure, crystallographic direction, atomic density, grain size, and atomic ordering (refs. 1 to 3).

Reference 2 clearly demonstrates the importance of crystal structure and lattice ratios on the frictional behavior of metals under sliding conditions in vacuum. For instance, cobalt exhibits an approximate fourfold increase in friction coefficient as the crystal structure changes from hexagonal to face-centered-cubic.

The effect of atomic ordering (the order-disorder transformation) on the frictional properties of alloys on the copper-gold system is presented in reference 4. In particular, the 50-atomic-percent copper - 50-atomic-percent gold alloy exhibits better than a six-fold increase in friction coefficient as the alloy goes from the ordered state to the disordered state.

The objectives of this investigation were to determine the effect on friction and wear of (1) crystal transformations for beryllium-cobalt alloy (Be-Co), and (2) the effect of the order-disorder transformation for an iron-cobalt alloy (FeCo) under sliding conditions in vacuum. The alloys investigated were 10-atomic-percent beryllium - 90-atomic-percent cobalt alloy, and 50-atomic-percent iron - 50-atomic-percent cobalt alloy.

CRYSTAL STRUCTURE AND ORDER-DISORDER TRANSFORMATIONS

Transformation is a term used to mean any extensive rearrangement of atomic structure. Crystal transformations are then the rearrangement of atoms from some fixed positions. This results in a transformation from one type of crystal structure to another, for example, hexagonal to face-centered-cubic. The property of a material to exist in two or more types of structure is known as polymorphism (ref. 5). There are many metals which exhibit these structural changes, which are highly temperature dependent (e.g., the rare earth metals lanthanum, cerium, praseodymium, and neodymium). Lanthanum, for instance, transforms from the hexagonal structure at room temperature to a face-centered-cubic structure at 590° F (310° C), and further changes to a body-centered-cubic structure at 1587° F (864° C) (ref. 6). Some of the more common metals such as titanium and cobalt also exhibit crystal transformations. Cobalt transforms from a hexagonal structure to a face-centered-cubic structure at 785° F (417° C). Small amounts of alloying agents may alter these transformation temperatures (refs. 2 and 7).

The order-disorder transformation is a change in the atomic arrangement in a substitutional type of solid solution. In an ordinary solid solution, the solute atoms will be distributed at random in the lattice of the solvent metal. This random arrangement is called the disordered condition. Certain solid solutions like copper-gold, when cooled slowly, will undergo a rearrangement of atoms such that solute atoms occupy definite lattice positions in the solvent metal. This preferential arrangement of solute atoms in the solvent lattice is called the ordered condition and the resulting structure is called a

superlattice (ref. 5). This phenomenon was first observed by Kurnahov in 1914 while working with copper-gold alloys. For each ordered alloy there is some critical temperature called the Kurnahov point at which the ordered structure will transform to the disordered state (ref. 8).

There are several alloy systems in addition to copper-gold that exhibit the order-disorder transformation, such as nickel-aluminum, cobalt-aluminum, cobalt-palladium, and FeCo. Not all of these alloys transform in the same manner from the ordered to the disordered state. The two ordering mechanisms of concern in this paper are the first-degree order mechanism, of which the copper-gold alloy (Au_3Cu) is an example, and the second-degree order mechanism, of which the iron-cobalt alloy (FeCo) is an example (refs. 9 and 10). The characteristic difference between these two order mechanisms is the way in which the degree of order varies as the Kurnahov point is approached. The Bragg-Williams parameter S is used to denote the degree of order based on the probability of particular lattice sites being filled with either A or B atoms in a binary AB alloy. For a fully ordered structure, $S = 1.0$, and for complete disorder, $S = 0$. The manner in which the degree of order changes for both first- and second-degree order transformations as the critical temperature is approached is discussed in reference 9.

MATERIALS

The Beryllium-Cobalt Alloy

The crystal transformation of cobalt from a hexagonal structure to a face-centered-cubic structure results in a marked increase in friction coefficient (ref. 2). As shown in figure 1, cobalt will readily weld in vacuum in the cubic form. Furthermore, the wear

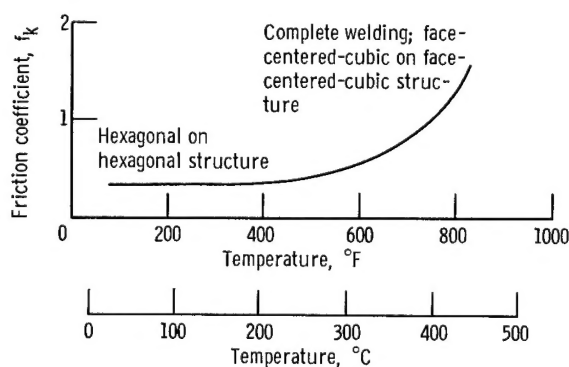
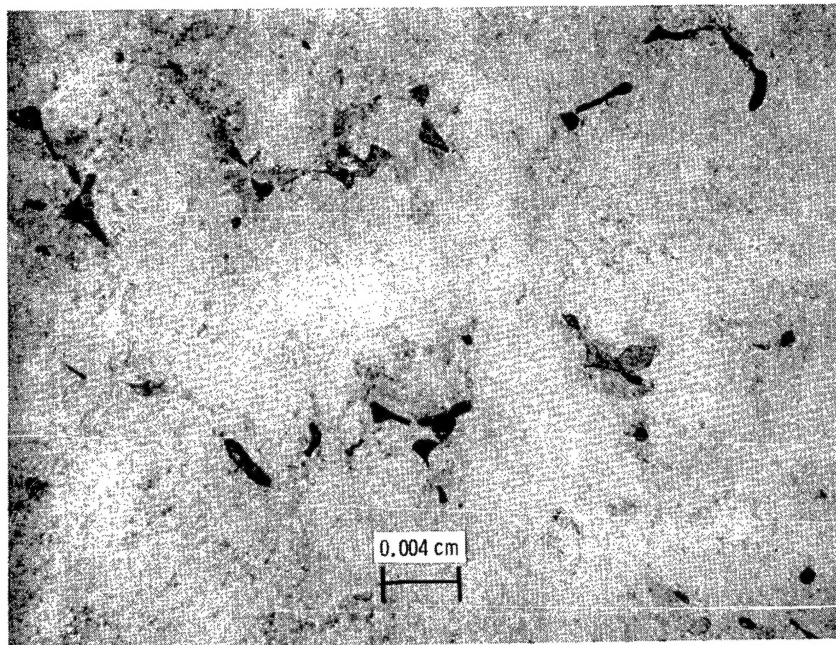
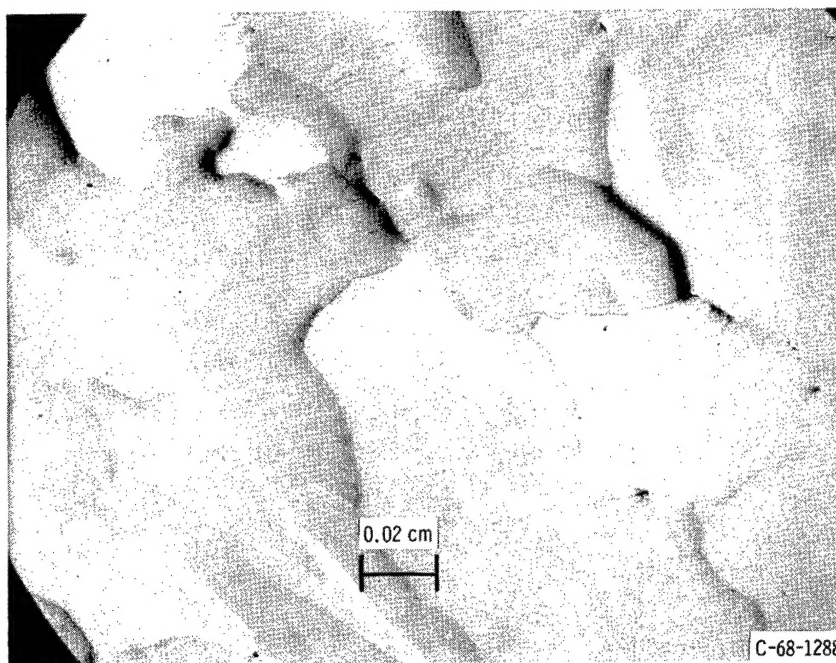


Figure 1. - Friction coefficient at various ambient temperatures for cobalt sliding on cobalt in vacuum. Pressure, 10^{-8} to 10^{-7} torr (10^{-6} to 10^{-5} N/m²); sliding velocity, 198 centimeters per second; load, 1 kilogram (figure taken from ref. 2).



(a) Beryllium-cobalt; nital etchant.



(b) Iron-cobalt; nital etchant.

Figure 2. - Beryllium-cobalt and iron-cobalt microstructures after heat treating.

of cobalt in the face-centered-cubic form has been reported to be approximately 100 times the hexagonal wear values (ref. 2). The hexagonal to face-centered-cubic transformation for cobalt takes place at approximately 785° F (417° C) (ref. 7). Consequently, the usefulness of cobalt as a member of a sliding or rotating systems is limited by this temperature.

The literature indicates that a small addition of beryllium to cobalt will shift the hexagonal to face-centered-cubic transformation temperature upward and will shift the reverse, or cooling transformation (face-centered-cubic to hexagonal) temperature downward. Specifically, the addition of 1.67-weight-percent beryllium (10 atomic percent) shifts the hexagonal to face-centered-cubic transformation temperature from 785° F (417° C) to 1022° F (550° C) (ref. 11). This increase in transformation temperature consequently increases the temperature range in which the cobalt system can be used in a mechanical situation.

Castings of 10-atomic-percent beryllium and 90-atomic-percent cobalt were made. The Be-Co alloy was vacuum cast at a pouring temperature of 2730° F (1499° C). The castings were then annealed at 1976° F (1080° C) and followed by an oil quench to produce a Rockwell C hardness of 10. Subsequent aging at 1157° F (625° C) brought the average Rockwell C hardness levels up to 44. The rider and disk were then ground to the specified dimensions with a surface finish being 4 to 8 rms. Chemical analysis of a cast sample showed the composition to contain 1.38-weight-percent beryllium; the maximum impurity being less than 0.05-weight-percent nickel. Photomicrographs showing the microstructure of the Be-Co alloy are shown in figure 2(a).

Iron-Cobalt Alloy

Figure 3 shows the pronounced increase in friction for the 50-50 atomic percent copper-gold during the order-disorder transformation. The copper-gold system is a classic example of atomic ordering and superlattice formation. The system, however, has little to offer in terms of practical mechanical application. Alloys of iron and cobalt are widely used. Therefore, the effect of atomic ordering of alloys on the iron-cobalt system may be more useful for practical applications.

The 50-50 atomic percent iron-cobalt alloy is a solid solution which exhibits the order-disorder transformation in the alpha phase. Reference 12 established the critical temperature for the order-disorder transformation for FeCo as being 1350° F (732° C) by thermal analysis and X-ray diffraction.

Thus, to investigate the order-disorder transformation on FeCo, specimens were prepared in the 50-50 atomic percent range. The FeCo was vacuum cast at a pouring temperature of 2600° F (1427° C). After casting, the specimens were annealed at

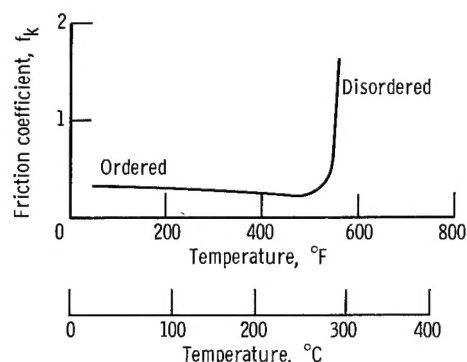


Figure 3. - Friction coefficient for copper-gold alloy sliding on 440-C stainless steel. Sliding velocity, 198 centimeters per second; load, 1 kilogram; pressure 10^{-9} to 10^{-7} torr (10^{-7} to 10^{-5} N/m²) (figure taken from ref. 4).

1850° F (1010° C) for 4 hours and at 1500° F (816° C) for 2 hours. The castings were then machined into final specimen configuration with surface finish being 4 to 8 rms. Photomicrographs taken after the anneal are shown in figure 2(b). Hardness of the annealed material was 91 Rockwell B. Chemical analysis of a cast sample showed the composition to be 49.40-weight-percent iron and 50.45-weight-percent cobalt. According to reference 13, this composition is in the range in which the FeCo superlattice does exist.

APPARATUS

The friction and wear experiments were conducted in the vacuum friction apparatus shown in figure 4. The test specimens were a 6.5-centimeter-diameter flat disk and a 0.476-centimeter-radius rider specimen. The disk was mounted horizontally on a shaft inside the chamber. The shaft was driven by a magnetic drive coupling consisting of two 20-pole magnets, one mounted inside the chamber, the other outside. The total clearance between the magnet faces was 0.381 centimeter with a 0.076-centimeter diaphragm between for sealing the vacuum chamber. Connected to the outer magnet was a drive shaft which was driven by a variable-speed electric motor for slow speed runs. A hydraulic motor was used for the higher speed runs. Test speeds were from 0.003 to 205 centimeters per second.

The rider specimen was mounted in a holder which bolts to a bellows-sealed gimbal-mounted, load arm. The load arm was used to apply the normal specimen load by dead-weight loading and also to transmit the friction force to a strain-gage assembly mounted outside the system. The strain-gage output was read out on a multirange potentiometer.

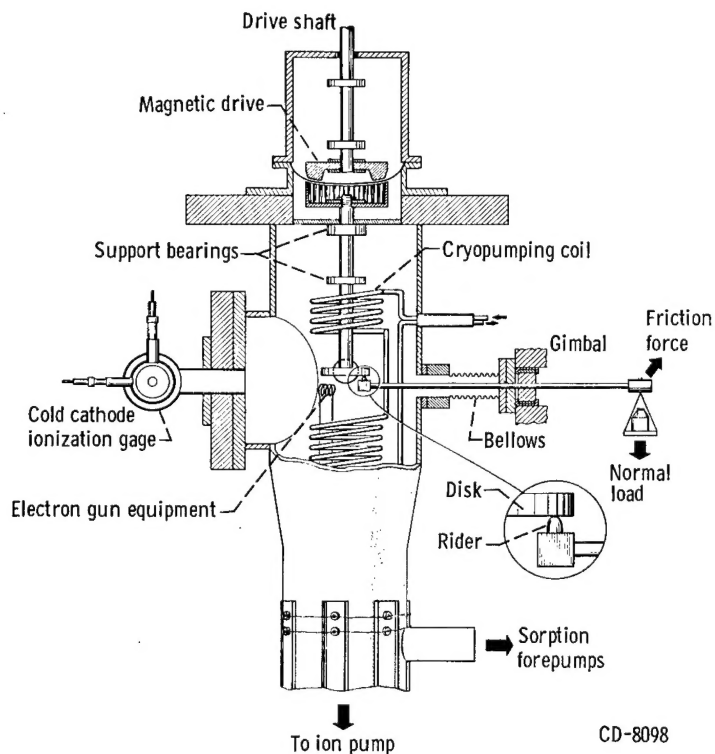


Figure 4. - Vacuum friction apparatus.

Attached to the lower end of the chamber were sorption pumps and a 400-liter-per-second ion pump. The sorption pumps were used to rough pump the system to 1 micrometer ($1.3 \times 10^{-1} \text{ N/m}^2$) at which pressure the ion pump was started. The ultimate pressure of the system with liquid-helium cryopumping is 10^{-11} torr (10^{-9} N/m^2), without cryopumping, 10^{-9} torr (10^{-7} N/m^2). This system is free from organic contaminants that might result from mechanical or diffusion pumping.

For heating the specimen, a 3.5-kilovolt, 500-milliampere electron gun was used. The electron gun filament was located within 0.63 centimeter of the rider-disk contact zone. The specimen temperature was measured with a chromel-alumel thermocouple located on the rider specimen approximately 0.32 centimeter from the rider-disk contact area. The pressure in the test chamber at the start of elevated temperature runs was 10^{-9} torr (10^{-7} N/m^2) but increased to 10^{-7} torr (10^{-5} N/m^2) while heating to maximum temperatures.

PROCEDURE

After machining to final configuration, the specimens were electropolished to remove the severely deformed layer that was present. The Be-Co alloy specimens were electro-

polished in a 50-50-volume-percent solution of orthophosphoric acid and glycerol. The FeCo alloy specimens were polished in a 20 - 80-volume-percent solution of perchloric acid and orthophosphoric acid.

After electropolishing, the specimens were rinsed with tap water, dried, and then soaked in acetone prior to insertion into the vacuum chamber. The specimens were removed from the acetone, dried, and mounted in the chamber using procedures to prevent contamination. The system was then thoroughly purged with nitrogen and pump-down was initiated.

Following system pumpdown and bakeout, the mounted specimens were cleaned by electron bombardment, the temperature rising to 750° F (400° C). The specimens were then cooled to room temperature. If the experiment was to be run at room temperature, liquid-helium cryopumping was begun, and the experiment started when the chamber pressure reached 10^{-11} torr (10^{-9} N/m²). For elevated temperature runs, no cryopumping was used, and the experiments were started on cooling to room temperature. Without cryopumping, the initial pressure was 10^{-9} torr (10^{-7} N/m²) but increased during heating to 10^{-7} torr (10^{-5} N/m²).

RESULTS AND DISCUSSION

The Beryllium-Cobalt Alloy

The effect of crystal structure on friction and wear properties of cobalt has been clearly demonstrated.

The addition of 1.38-weight-percent beryllium increases the crystal transformation temperature of cobalt by 237° F (133° C), consequently, raising the temperature at which the friction should be affected. This expected effect is shown clearly in the friction data presented in figure 5. Light loads and low sliding speeds were used for these data

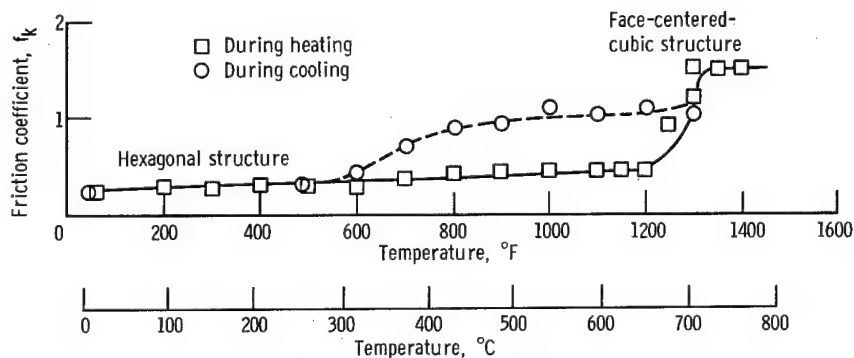


Figure 5. - Coefficient of friction for beryllium-cobalt sliding on beryllium-cobalt. Sliding velocity, 0.003 centimeter per second; load, 125 grams; pressure 10^{-9} to 10^{-7} torr (10^{-7} to 10^{-5} N/m²).

to prevent addition of excessive frictional heating which may contribute to the transformation. A pronounced upward break in the friction-temperature curve occurred at approximately 1200°F (649°C). This temperature is far above the break point for the friction of pure cobalt. The 1200°F (649°C) break point (from fig. 5) is greater than the 1022°F (550°C) transformation temperature given in reference 11.

As with pure cobalt, the friction increased by a factor of 4 during transformation. The friction coefficient, during cooling, dropped slightly but remained about three times as high as pretransformation friction values; the friction remained high during cooling to about 600°F (316°C), then returned to the pretransformation value. It is to be expected that the friction would remain high until the reverse or cooling transformation

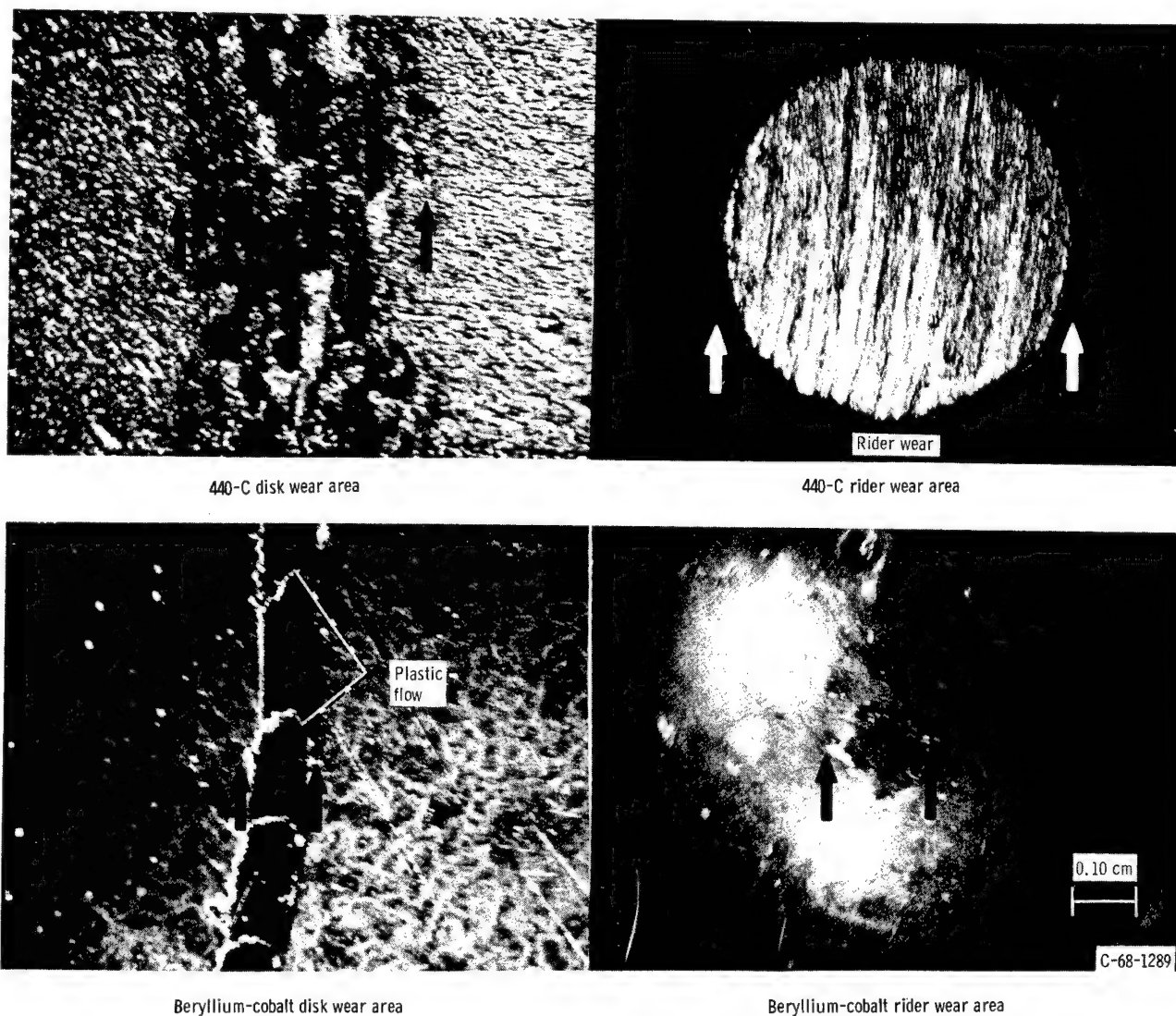


Figure 6. - Wear areas for 440-C stainless steel and beryllium-cobalt. Sliding velocity, 205 centimeters per second; load, 500 grams; pressure 10^{-11} torr (10^{-9} N/m²); duration, 1 hour.

(face-centered-cubic to hexagonal) takes place. With the addition of beryllium, the reverse transformation temperature drops from about 707° to 518° F (375° to 270° C) (ref. 11).

For comparison purposes, friction and wear runs were made at room temperature for the Be-Co alloy and a conventional bearing material, 440-C stainless steel. The wear of the Be-Co was 2.9×10^{-4} cubic centimeter as compared with 1.1×10^{-1} cubic centimeter for 440-C in 1-hour runs. Photographs of the rider and disk wear areas are shown in figure 6. Note the contrast in the wear area of the Be-Co disk and the 440-C disk. The Be-Co disk is characterized by plastic flow in the wear-track area, and the 440-C wear track is characterized by adhesive metal transfer. Also, the friction coefficient for the Be-Co alloy was less than one-half that of the 440-C stainless steel.

The Iron-Cobalt Alloy

The order-disorder transformation was shown in reference 4 to influence frictional behavior significantly for the copper-gold alloys Cu-Au and Cu_3Au . Like the 50-50 atomic CuAu alloy, the 50-50 atomic FeCo alloy undergoes ordering. The effect of the order-disorder transformation on frictional behavior of FeCo is of interest in view of the wide usage of ferrous alloys in mechanical application. Therefore, sliding friction

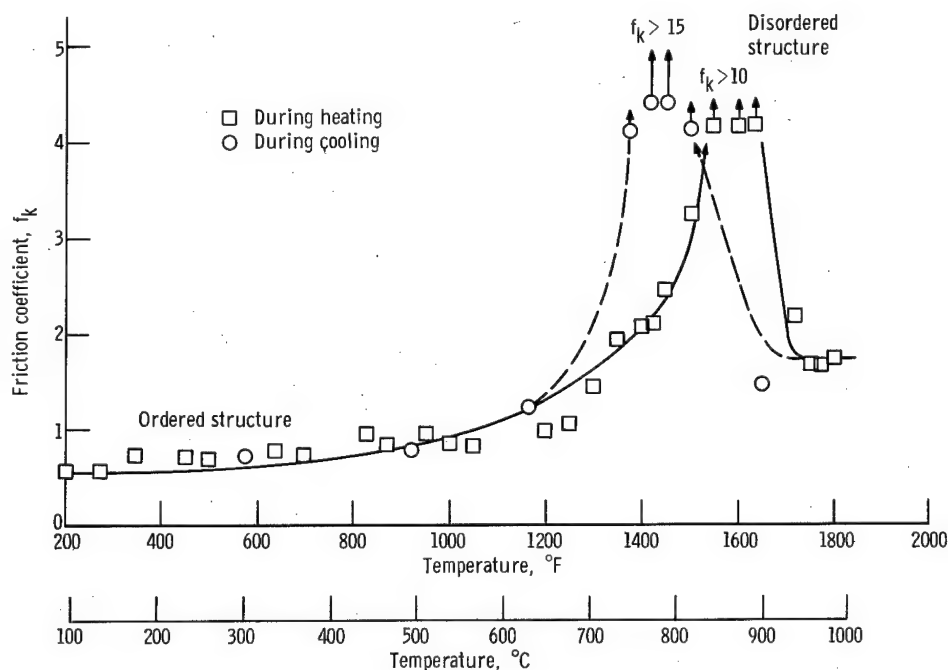
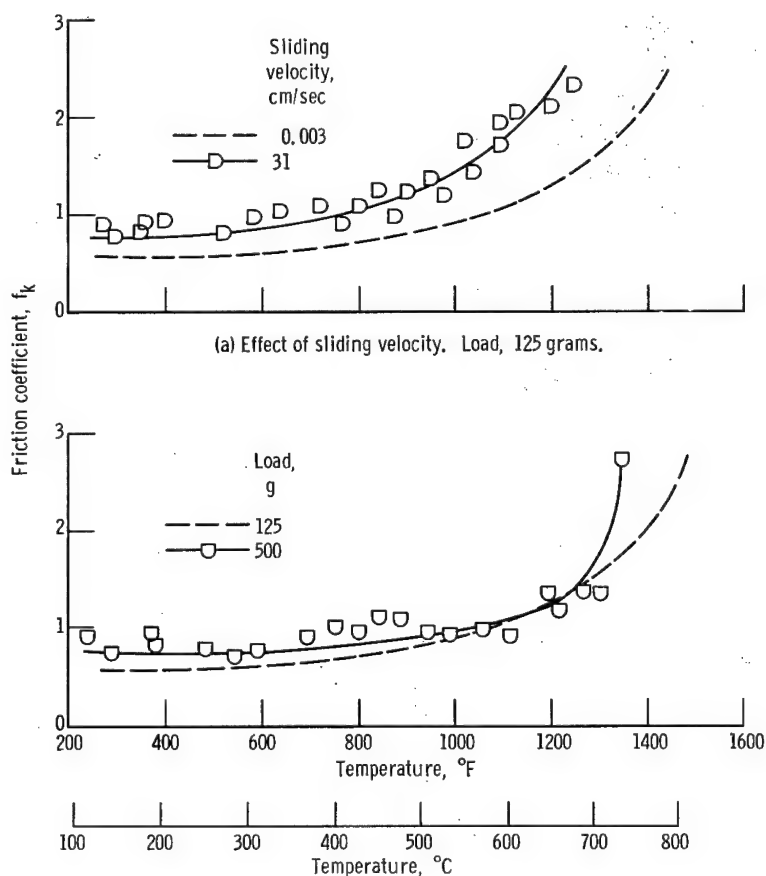


Figure 7. - Friction coefficient for iron-cobalt sliding on iron-cobalt at various temperatures. Sliding velocity, 0.003 centimeter per second; pressure 10^{-9} to 10^{-7} torr (10^{-7} to 10^{-5} N/m²); load, 125 grams.

experiments were conducted with FeCo in vacuum at elevated temperatures to study the effect of the order-disorder transformation on friction and wear.

Friction as a function of temperature is presented in figure 7. As with the Be-Co curve, these data were taken at light loads and slow surface speeds to avoid excessive frictional heating. Initially, the friction for FeCo sliding on FeCo was about 0.50, but as the temperature increased the friction began rising. At 1600° F (871° C), a friction coefficient greater than 10 was measured. This pronounced change in friction is due to the order-disorder transformation taking place in the FeCo. On further heating, a sharp drop in friction was observed, and at 1800° F (982° C), the friction coefficient was 1.8, a sharp contrast to the values measured at 1600° F (871° C). This drop in friction at the end of the temperature range may be due to a second transformation occurring in the FeCo alloy. References 11 and 14 show that at 1805° F (985° C), a second transformation occurs. This transformation is the alpha to gamma phase change (ferrite to austenite).

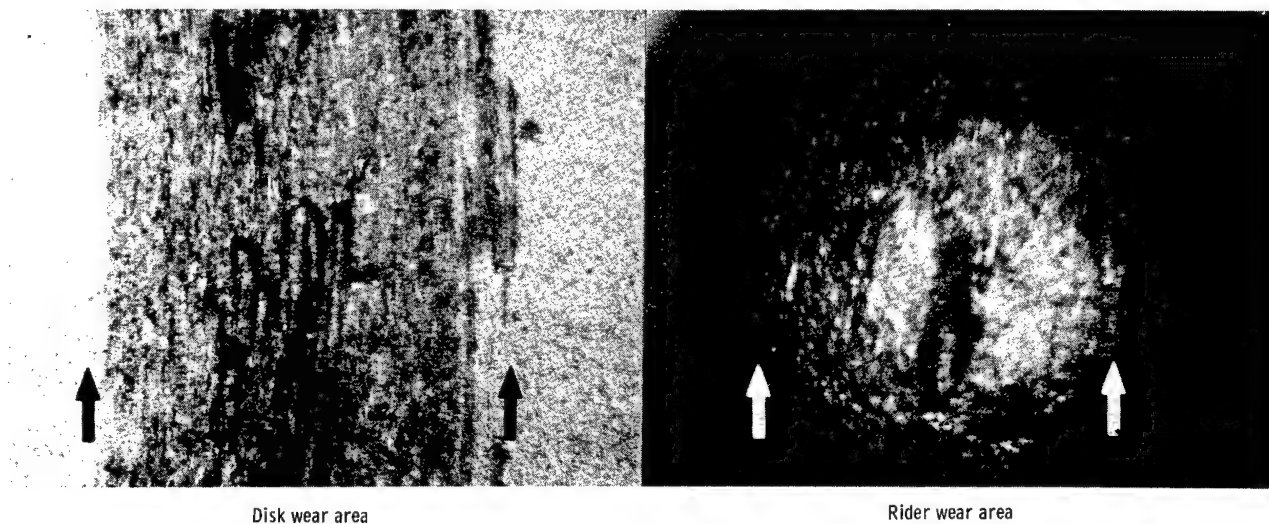
At 1800° F (982° C), heating was stopped, and the friction measured while the speci-



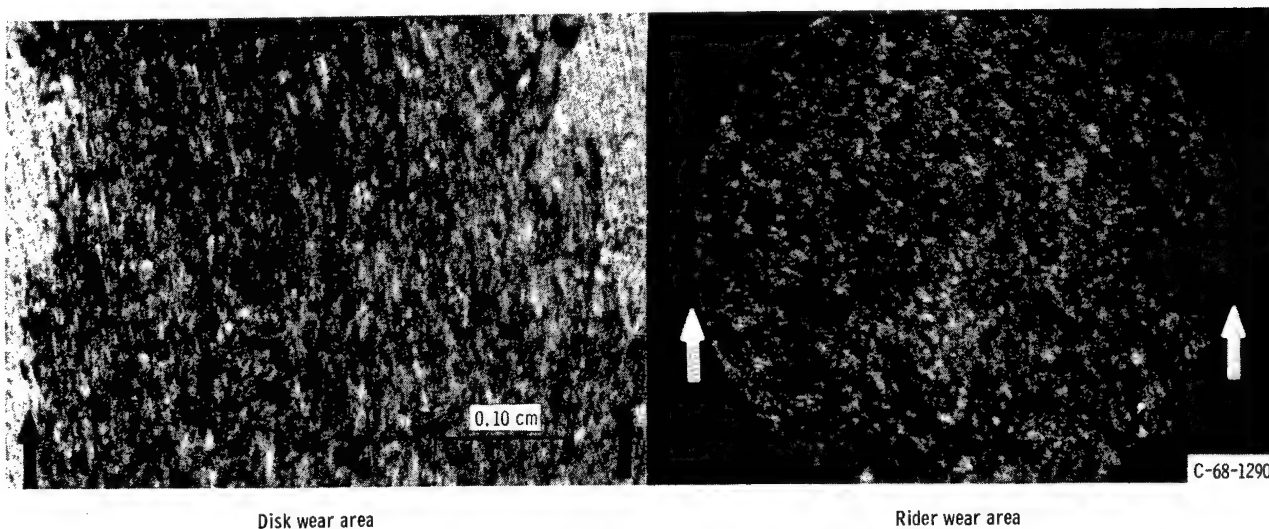
(a) Effect of sliding velocity. Load, 125 grams.
(b) Effect of load. Sliding velocity, 0.003 centimeter per second.
Figure 8. - Effect of sliding velocity and load on friction for iron-cobalt sliding on iron-cobalt. Pressure, 10^{-9} to 10^{-7} torr (10^{-7} to 10^{-5} N/m²).

mens slowly cooled. On cooling to 1600°F (871°C), the friction again increased, and at 1500°F (816°C), the friction coefficient was greater than 15 (fig. 7). At about 1400°F (760°C), friction started to drop, and with further cooling, the friction eventually returned to the pretransformation level. The lag in the cooling curve as compared with the heating curve suggests a time dependency for both transformations.

In order to determine the effect of sliding velocity and load on the friction-temperature dependency, friction data were taken at higher sliding velocities and higher loads. The results are shown in figure 8. Increased sliding velocity had a significant effect on the friction-temperature relation. Increased sliding velocity tends to add func-



(a) Run temperature, 75°F (24°C); ordered structure.



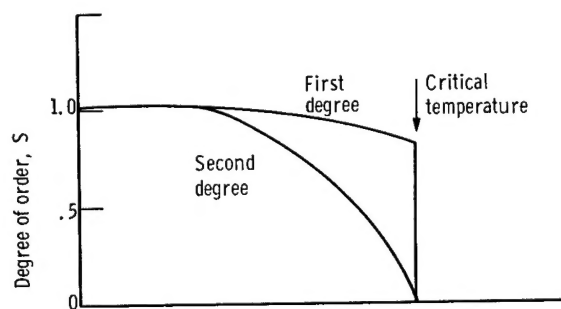
(b) Run temperature, 1350°F (732°C); disordered structure.

Figure 9. - Iron-cobalt test specimens after 1-hour run. Load, 250 grams; sliding velocity, 31 centimeters per second; pressure, 10^{-9} to 10^{-7} torr (10^{-7} to 10^{-5} N/m^2).

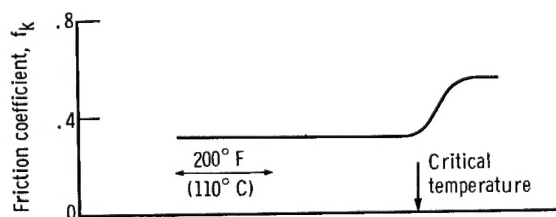
tional heating energy, consequently reducing the amount of external heating necessary to achieve transformation. Hence, the friction curve will rise at lower temperatures. Increased loading will also effect friction, but the load could only be increased by a factor of 4 whereas speed was increased by a factor of 10 000, as a result, the effect is not as readily observed.

To determine the effect of the order-disorder transformation on the wear properties of the FeCo, wear runs were made at room temperature (ordered condition) and at the critical temperature (disordered condition). Photographs of the wear areas are presented in figure 9. The wear of the ordered FeCo was 1.6×10^{-3} cubic centimeter, and the wear of the disordered FeCo was 2.5×10^{-2} cubic centimeter, a fifteen fold difference.

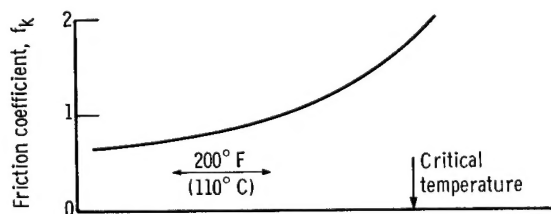
As mentioned above, the FeCo solid solution is an example of second-degree order while the Cu_3Au is an example of first-degree order. Figure 10(a) presents general



(a) Typical variation in degree of order with temperature for first- and second-degree order.



(b) Variation in friction with temperature for copper-gold (first-degree order) alloy (from ref. 4).



(c) Variation in friction with temperature for iron-cobalt (second-degree order) alloy.

Figure 10. - Comparison curves for copper-gold and iron-cobalt alloys with regard to type of order.

curves showing how the degree of order changes as the critical temperature is approached for both first- and second-degree order. For first-degree order, S will decrease slowly, on heating, to about 0.8, and then, at the critical temperature drop, to 0. For second-degree order, S will decrease continuously from 1.0 to 0 as the critical temperature is approached (ref. 9). Thus, it might be expected that the effect of the transformation on frictional behavior for the first-degree order alloy, Cu_3Au , would be abrupt, and for a second-degree order type FeCo the effect should be more gradual. Figures 10(b) and (c) show that for Cu_3Au the increase in friction is abrupt and occurs in a relatively narrow temperature range, although for the FeCo , the change in friction is gradual over a wider temperature range. This is in excellent agreement with the type of order exhibited by each alloy.

SUMMARY OF RESULTS

Friction and wear experiments conducted in vacuum with the beryllium-cobalt and iron-cobalt alloys yielded the following results:

For the beryllium-cobalt alloy (Be-Co):

1. The transformation from hexagonal to face-centered-cubic results in an increase, by a factor of 4, in the friction of a Be-Co alloy.
2. Once the hexagonal to face-centered-cubic transformation has taken place, the friction remains high until the Be-Co alloy is cooled below the reverse or cooling (face-centered-cubic to hexagonal crystal) transformation temperature.
3. The increase in transformation temperature of 237°F (133°C) for Be-Co results in a greater usable temperature range than for unalloyed cobalt in sliding conditions.
4. The wear of Be-Co was 2.9×10^{-4} cubic centimeter as compared with 1.1×10^{-1} cubic centimeter for a conventional bearing steel, 440-C.

For the Iron-Cobalt alloy (FeCo):

1. The order-disorder transformation in FeCo results in a thirtyfold increase in friction from the ordered state to the disordered state.
2. The wear properties of FeCo are also markedly increased by the order-disorder transformation. The wear increases by a factor of 15, from 1.6×10^{-3} cubic centimeter for the ordered structure to 2.5×10^{-2} cubic centimeter for the disordered structure.
3. Increased sliding speed and loading have the effect of lowering the temperature at which the friction begins to increase.

4. The gradual increase in friction for FeCo is in good agreement with the variation of order as the critical temperature is approached.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 3, 1968,
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